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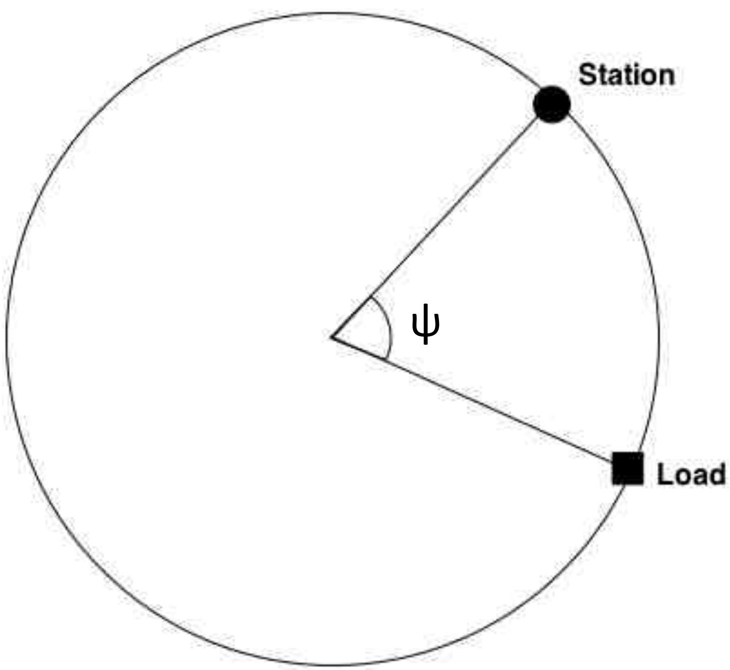
Mass Loading in VLBI Analysis

Overview

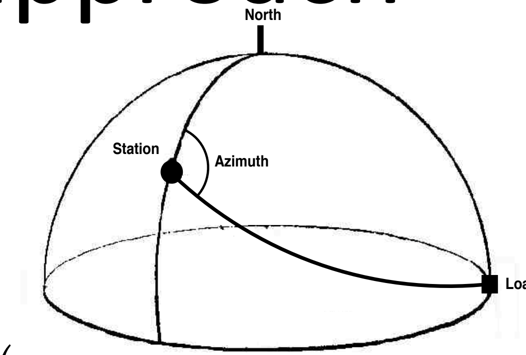
- Mass Loading
  - The Green's function approach
  - Loading algorithm
- Hydrology data
  - GLDAS NOAH Hydrology model
  - NASA GRACE GSFC mascons
- Hydrology Loading
  - Comparison of the hydrology loading series
  - Reduction in VLBI site position scatter
- Topographic errors in VLBI pressure loading series
  - Topographic variations on the surface of the earth
  - Height adjusting procedures
  - Peak-to-peak errors in vertical pressure loading series
  - Other sources of pressure

The Green’s function approach

- The Green’s function is the response at the station to a mass load.
- Depends on the angular distance between the load and the station.
- Convolve the loading Green’s function over the earth surface mass load to get the total response at the station.



The Green's function approach



- According to Farrell [1972] the displacements are given by
  - Vertical: $u_R(\vec{r}) = \iint\limits_S \Delta m(\vec{r}\,') \, G_R(\psi)\cos(\varphi')\,d\lambda' d\varphi'$
  - East-West: $u_{EW}(\vec{r}) = \iint\limits_S \Delta m(\vec{r}\,')\sin(A) G_H(\psi)\cos(\varphi')\,d\lambda' d\varphi'$
  - North-South: $u_{NS}(\vec{r}) = \iint\limits_S \Delta m(\vec{r}\,')\cos(A) G_H(\psi)\cos(\varphi')\,d\lambda' d\varphi'$
  - Vertical Green's function: $G_R(\psi) = \frac{Ga}{g_0^2}\sum_{n=0}^{+\infty} h_n' P_n(\cos\psi)$
  - Horizontal Green's function: $G_H(\psi) = -\frac{Ga}{g_0^2}\sum_{n=1}^{+\infty} l_n' \frac{\partial P_n(\cos\psi)}{\partial \psi}$

a=radius of the earth, G=universal constant of gravity,

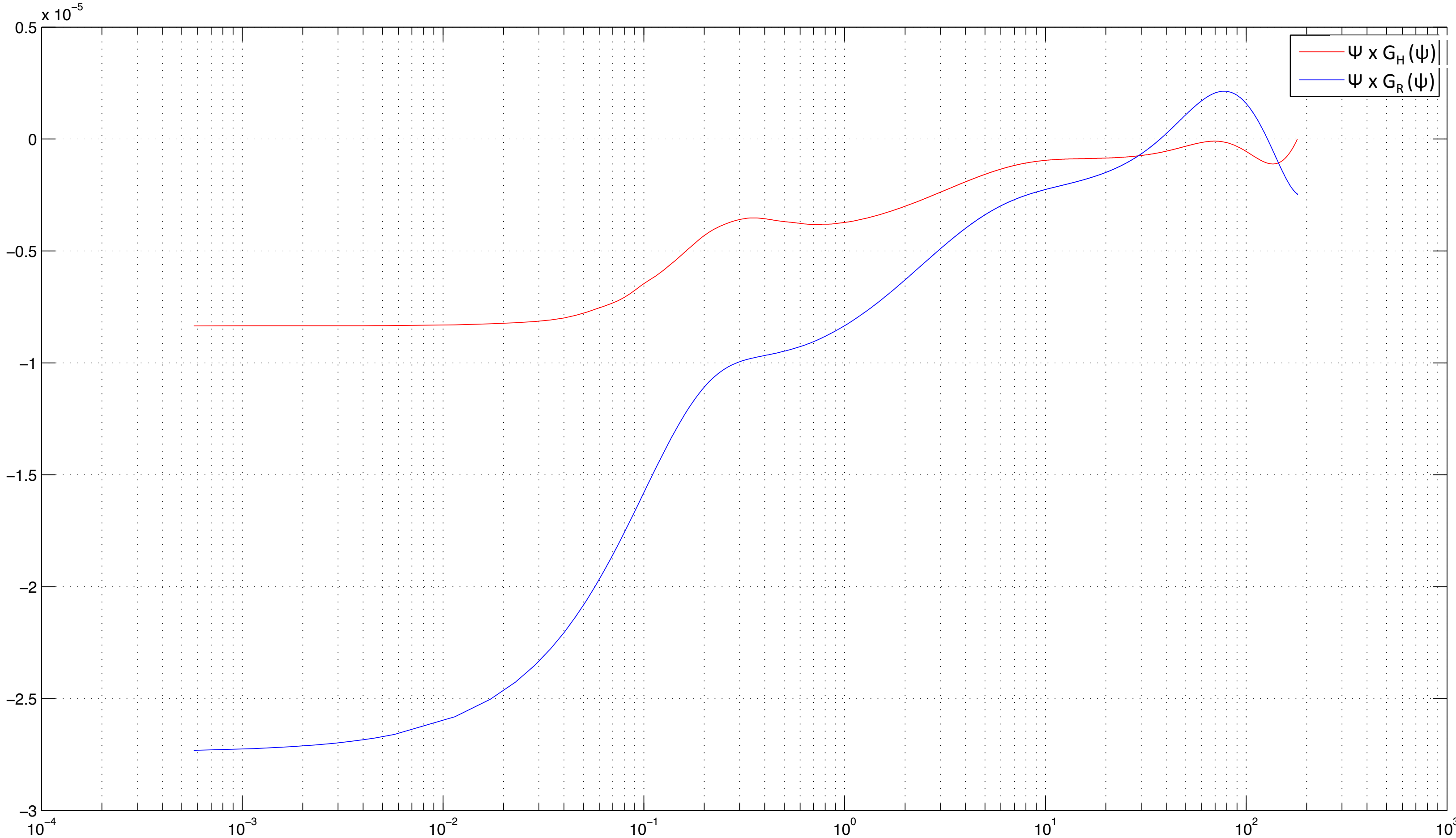
g_0=mean surface gravity, A=the azimuth, ψ=arc distance, Δm=change in mass

l_n' and h_n' are the load Love numbers computed for a spherically, nonrotating, elastic and isotropic Earth model.

The Green's function approach

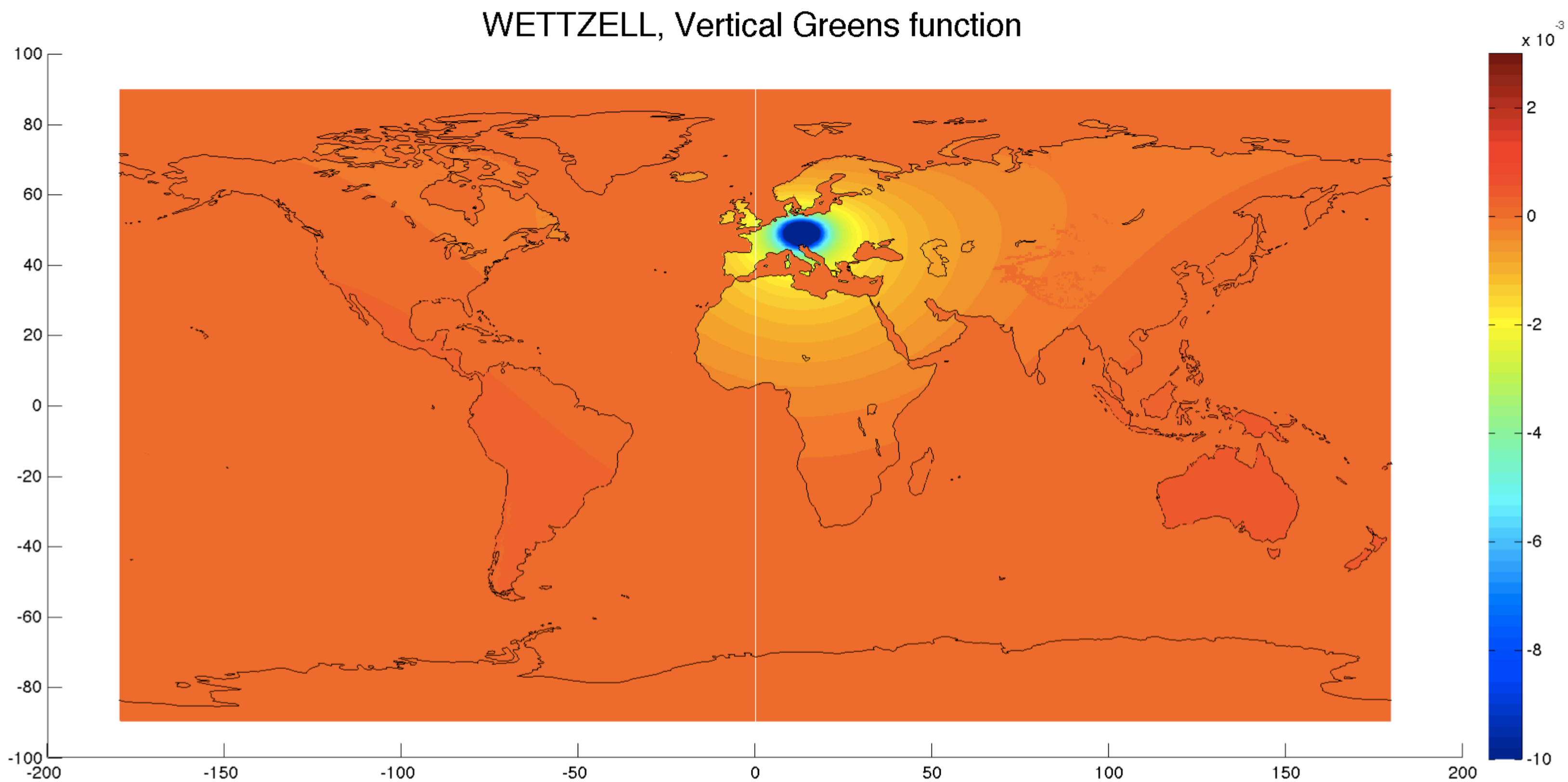
- The Green's functions are both singular (degree one) for $\psi=0$.
- The loading Green's function can't be expressed analytically using elementary functions
- Values are therefore pre-computed for $\psi * G(\psi)$ because of this singularity.
- Loading contribution is dominated by loading near the station and large coherent regional loads far from the station.

The Green's function approach

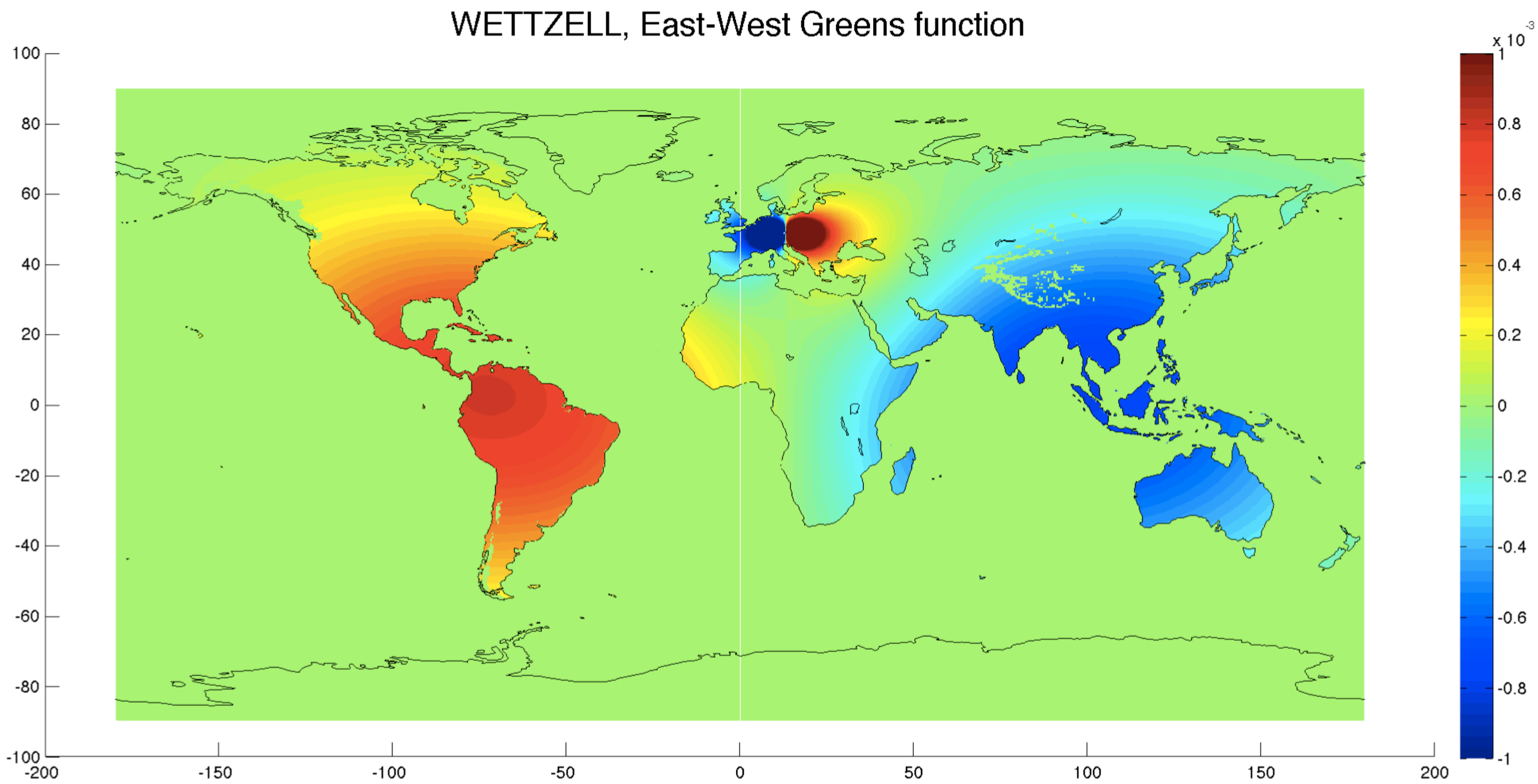


Ψ is given in degrees

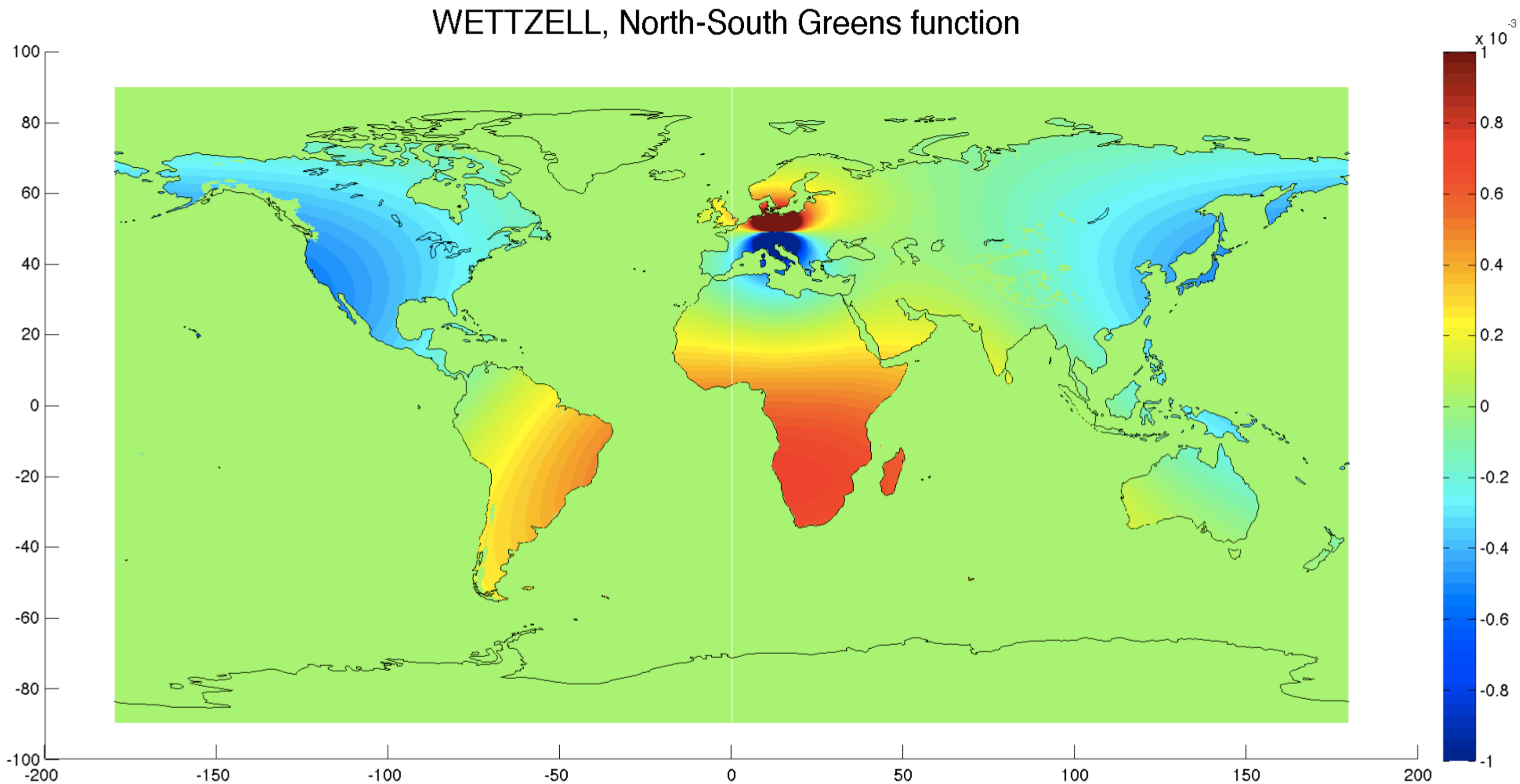
Wettzell, Vertical Green's function



Wettzell, East-West Horizontal Green's function



Wettzell, North-South Horizontal Green's function



Algorithm

- Divide the grid into three regions w.r.t. the site
  - 1) $10° < \psi < 180°$, refine to 0.05° x 0.05°
  - 2) $2° < \psi < 10°$, refine to 0.005° x 0.005°
  - 3) $0° < \psi < 2°$, refine to 0.001° x 0.001°
- Oceans + lakes + permanent ice are masked out
  - Resolution is 0.25° x 0.25°
- The loading displacements are calculated by summing up the loading from each cell by taking the value of the Green's function in the center of each cell

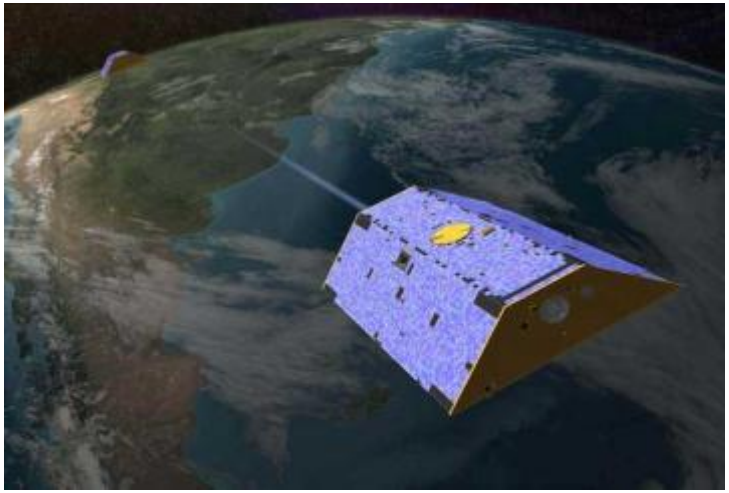
Hydrology Model

Computed hydrology loading series using

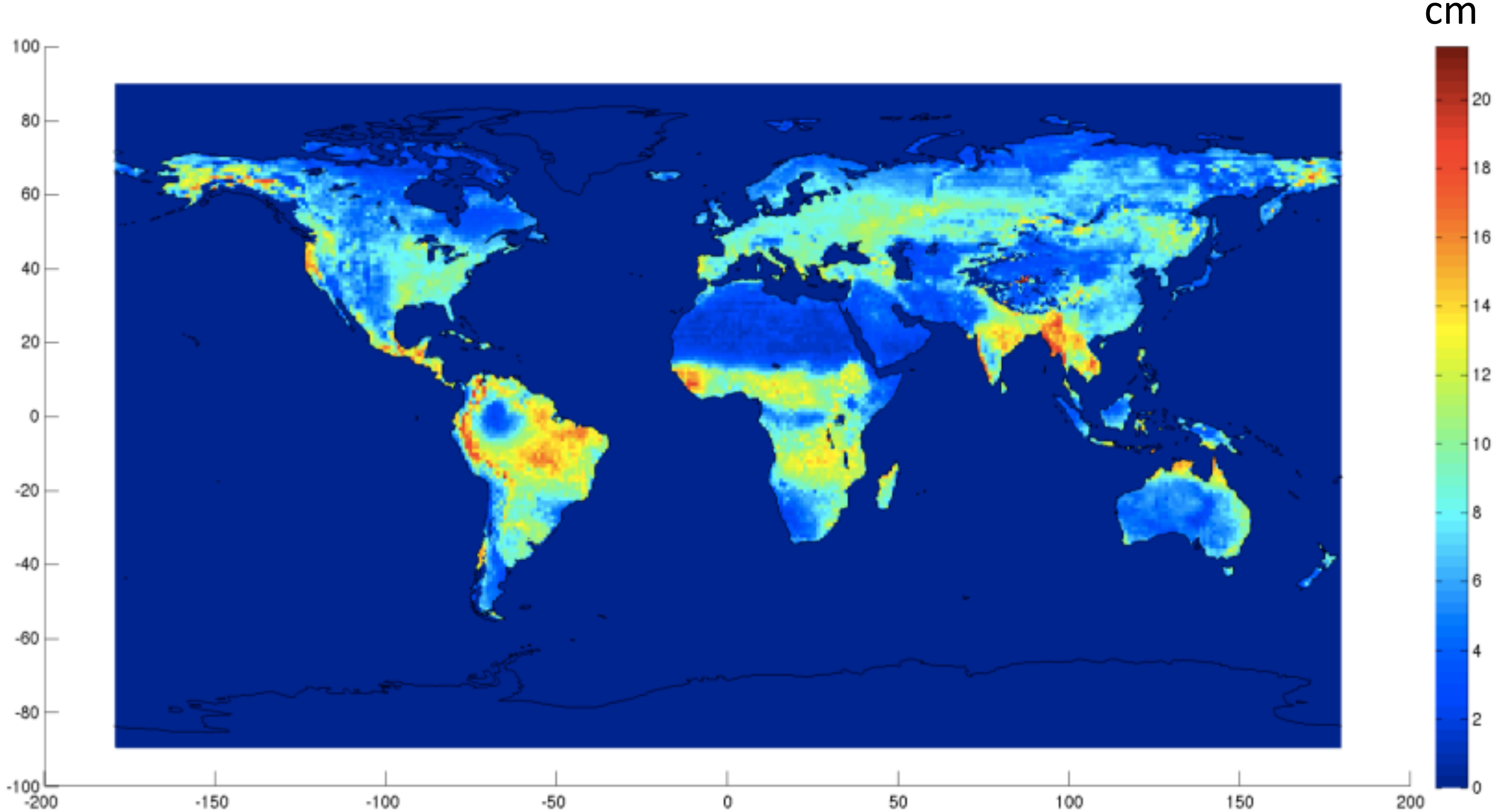
- Global Land Data Assimilation System (GLDAS) NOAH hydrology model [M. Rodell, GSFC]
  - 2m depth Soil moisture + Snow water equivalent
  - Not designed to model ground water or surface water
  - Doesn’t account for ice sheet processes.
  - Resolution is 0.25^{o} x 0.25^{o} with each third hour

NASA GSFC GRACE

- GRACE monitors the gravity field of the earth at a very high precision able to detect changes in groundwater stocks, mass changes within the oceans, and the mass balance over ice sheets.
- GRACE measures the total mass change.

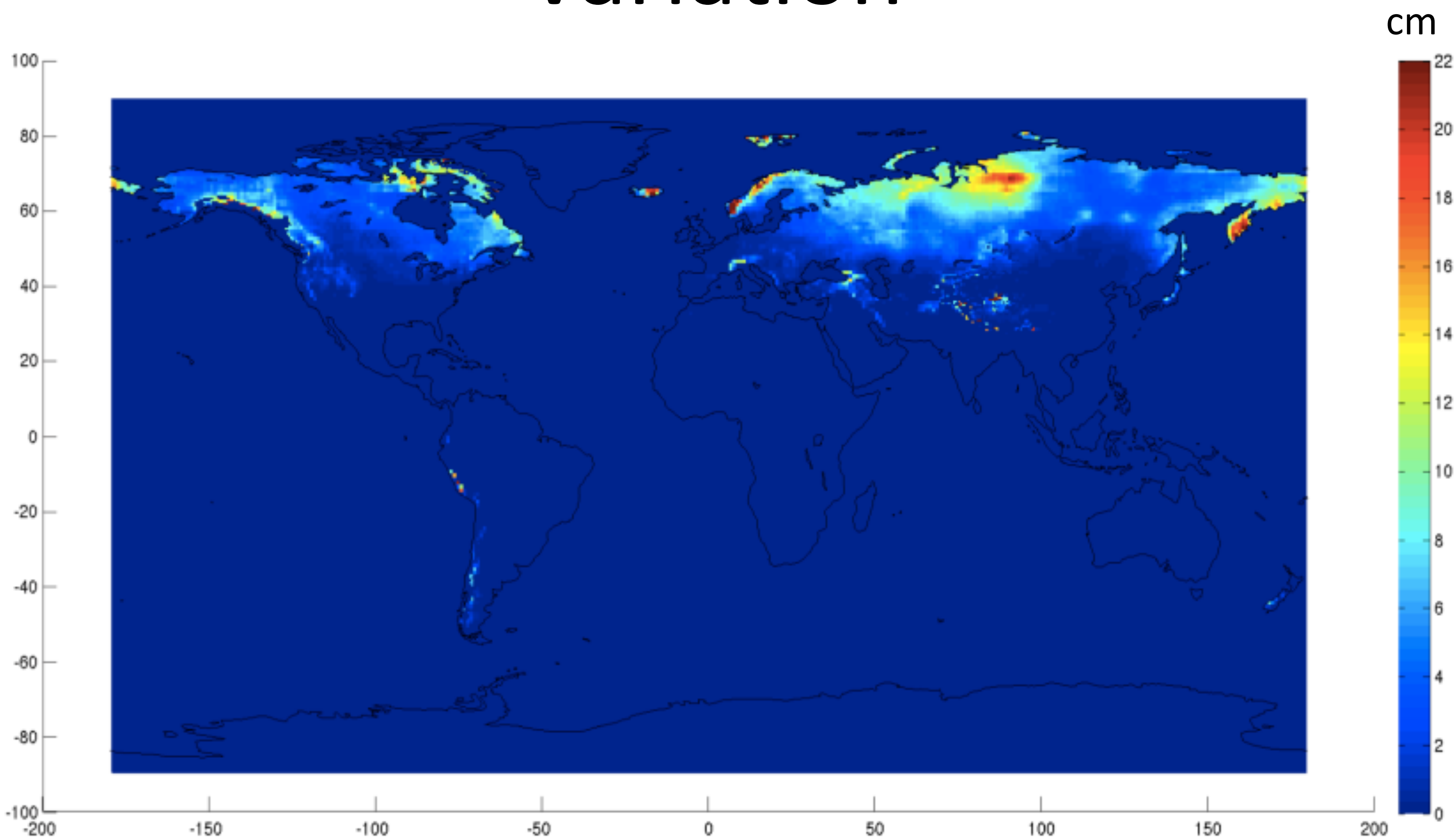


GLDAS 2-meter Soil moisture variation



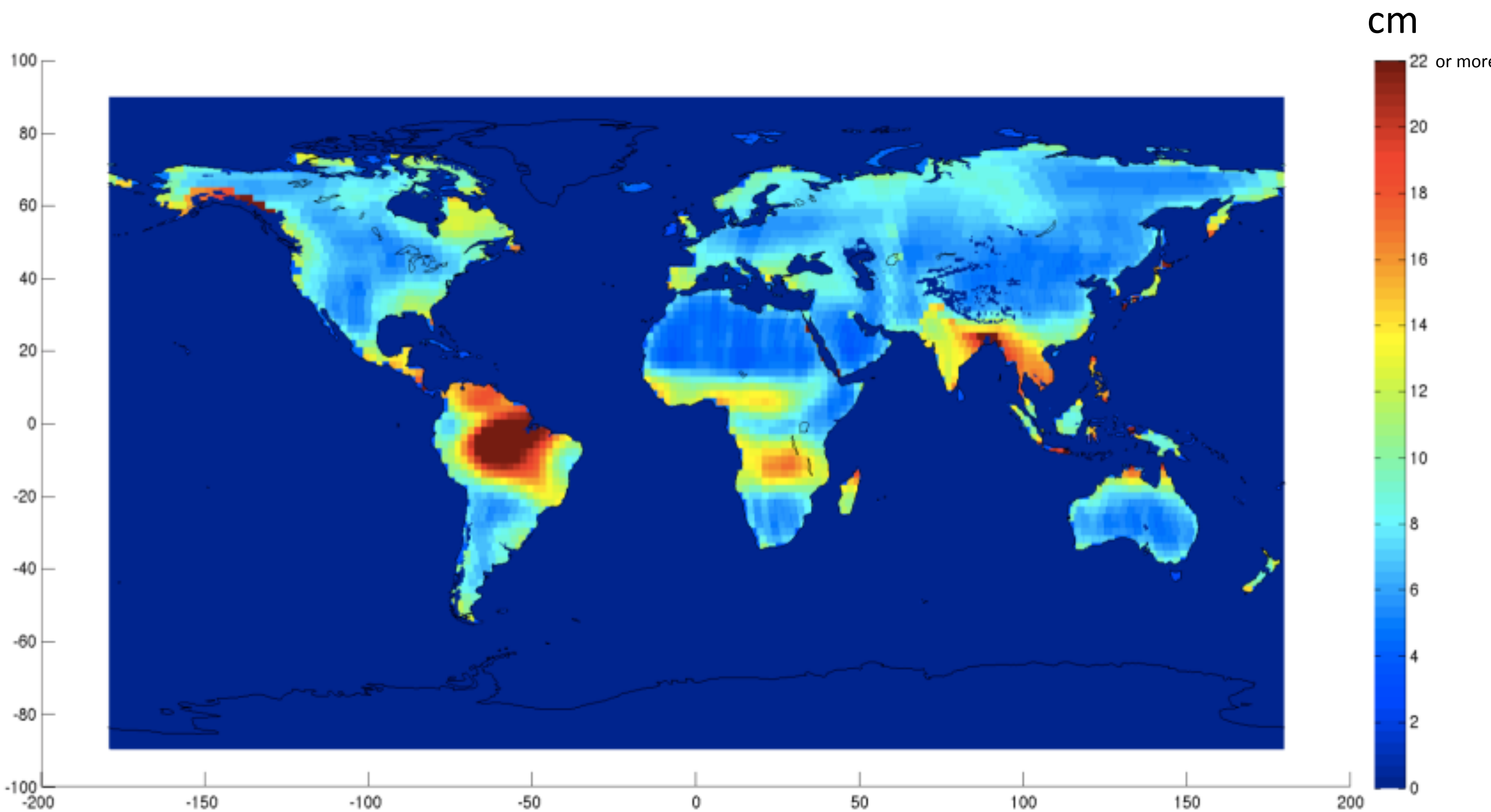
Standard deviation for each cell in cm of water

GLDAS Snow water equivalent variation



Standard deviation for each cell in cm of water

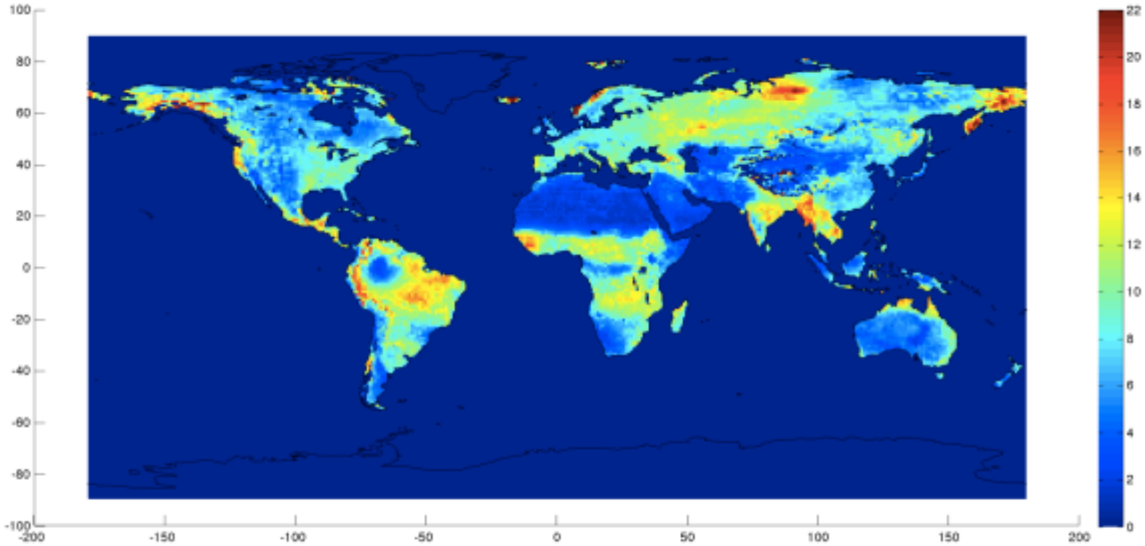
GRACE Mascons variation



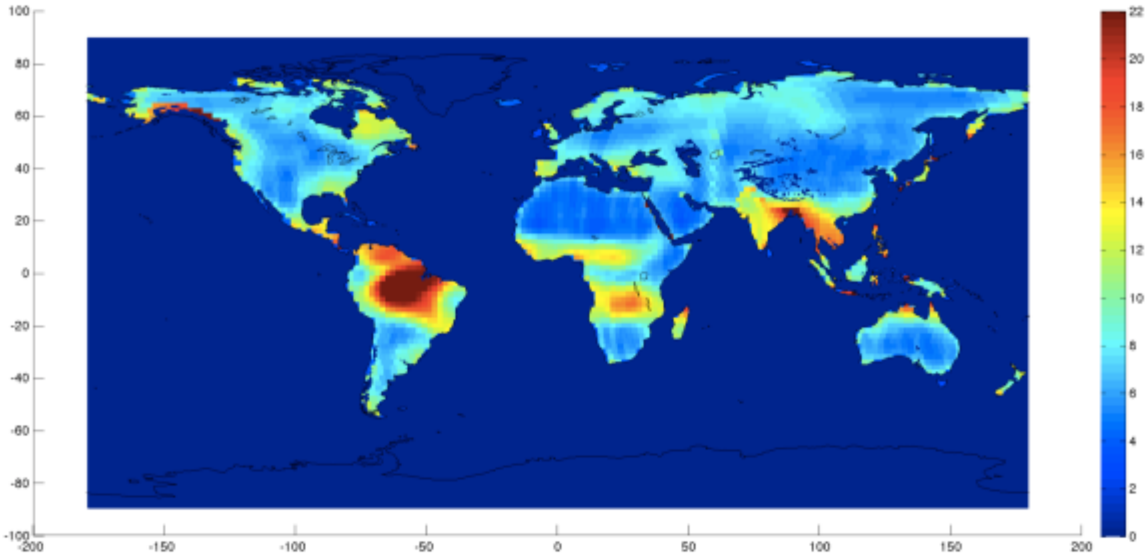
Standard deviation for each cell in cm of water

Hydrology data comparison

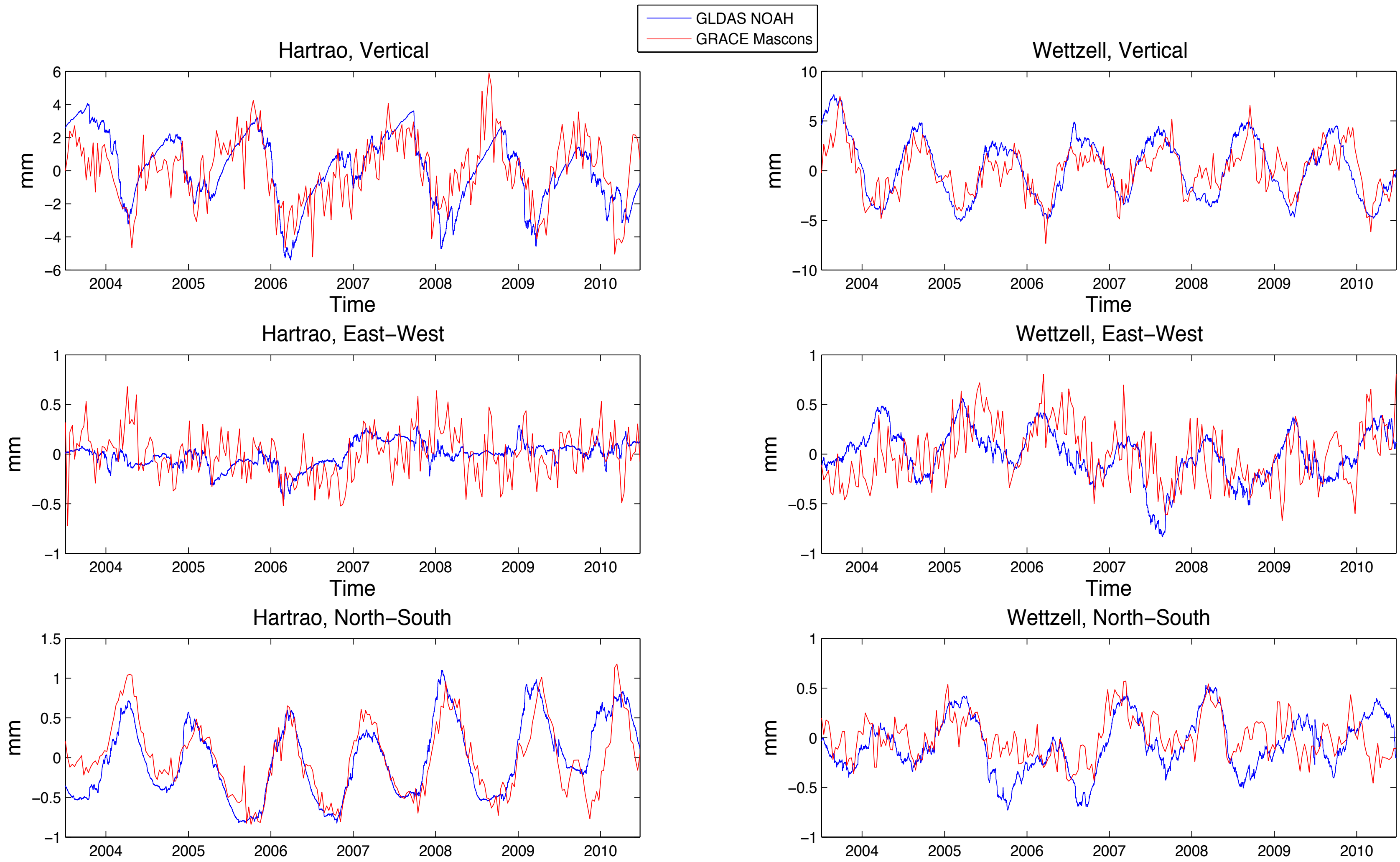
GLDAS NOAH



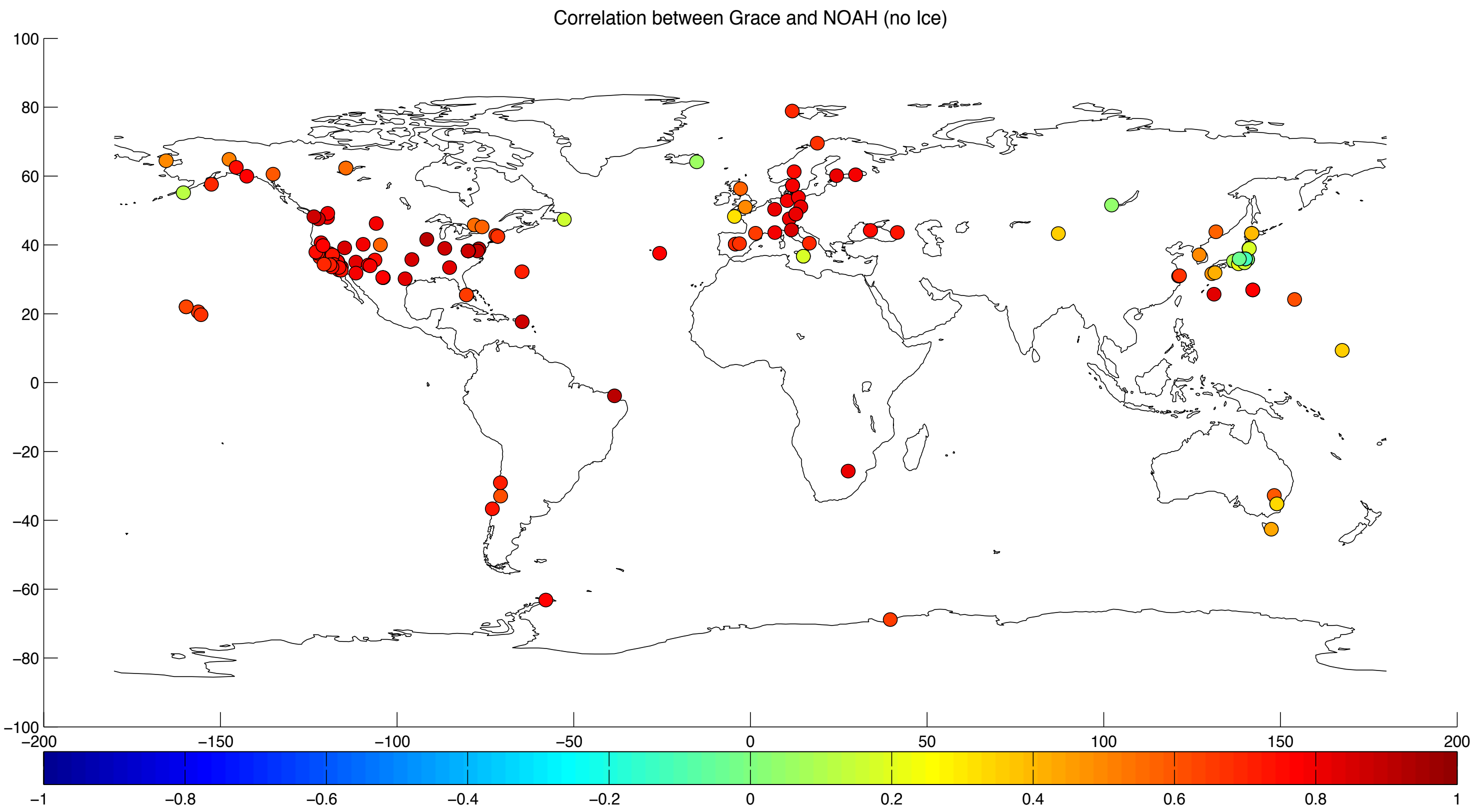
GRACE Mascons



Hydrology loading series



Correlation map between GRACE and GLDAS vertical loading series

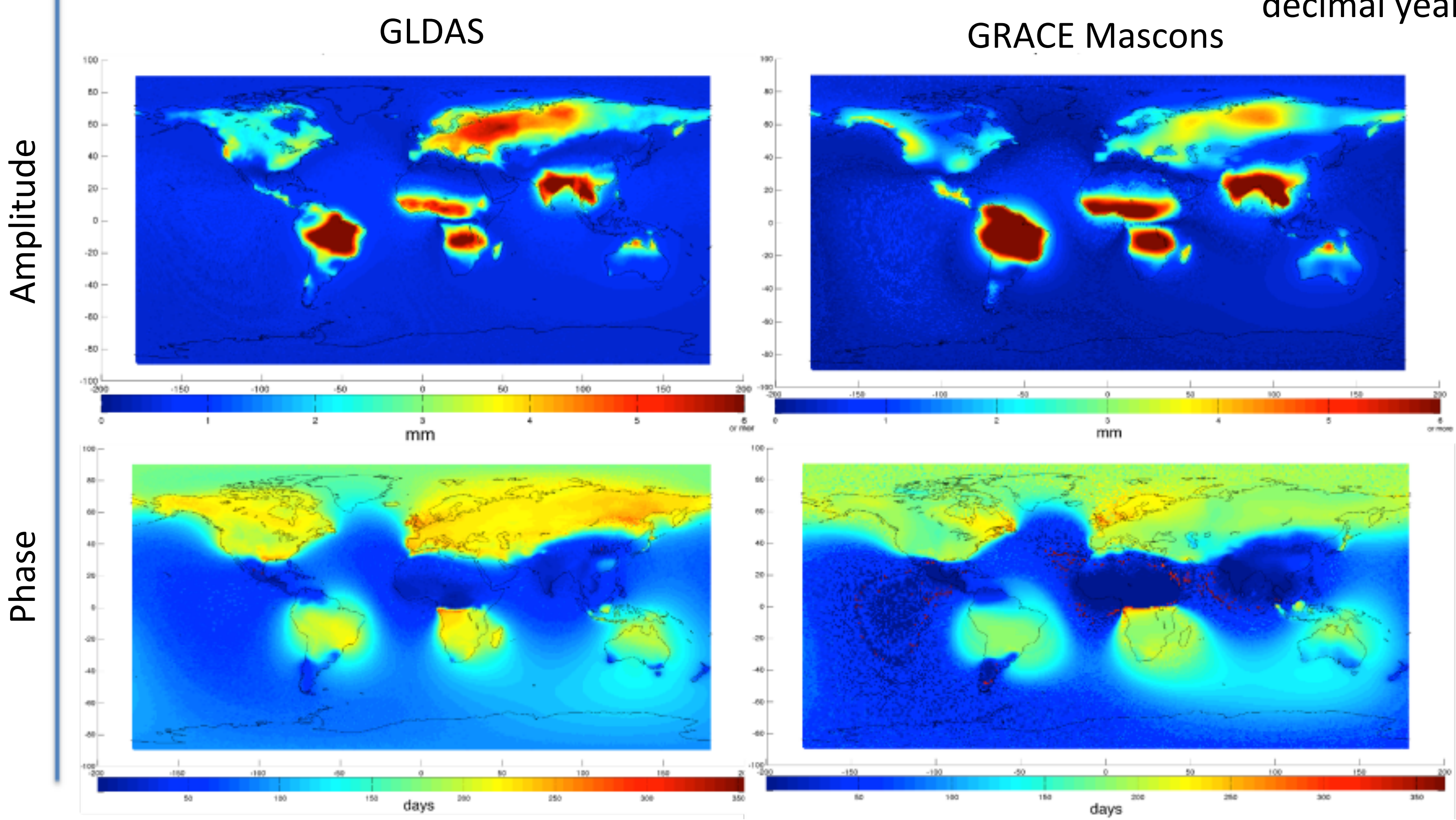


- Most of the sites with poor correlation are coastal or on islands
- Two inland sites, Badary and Urumqi, also show poor correlation

Amplitude & Phase plot

$$f(x) = a + bx + c\cos\left(2\pi\left[x + \frac{d}{365.25}\right]\right), c > 0, d \in [0, 365.25)$$

x is the decimal year



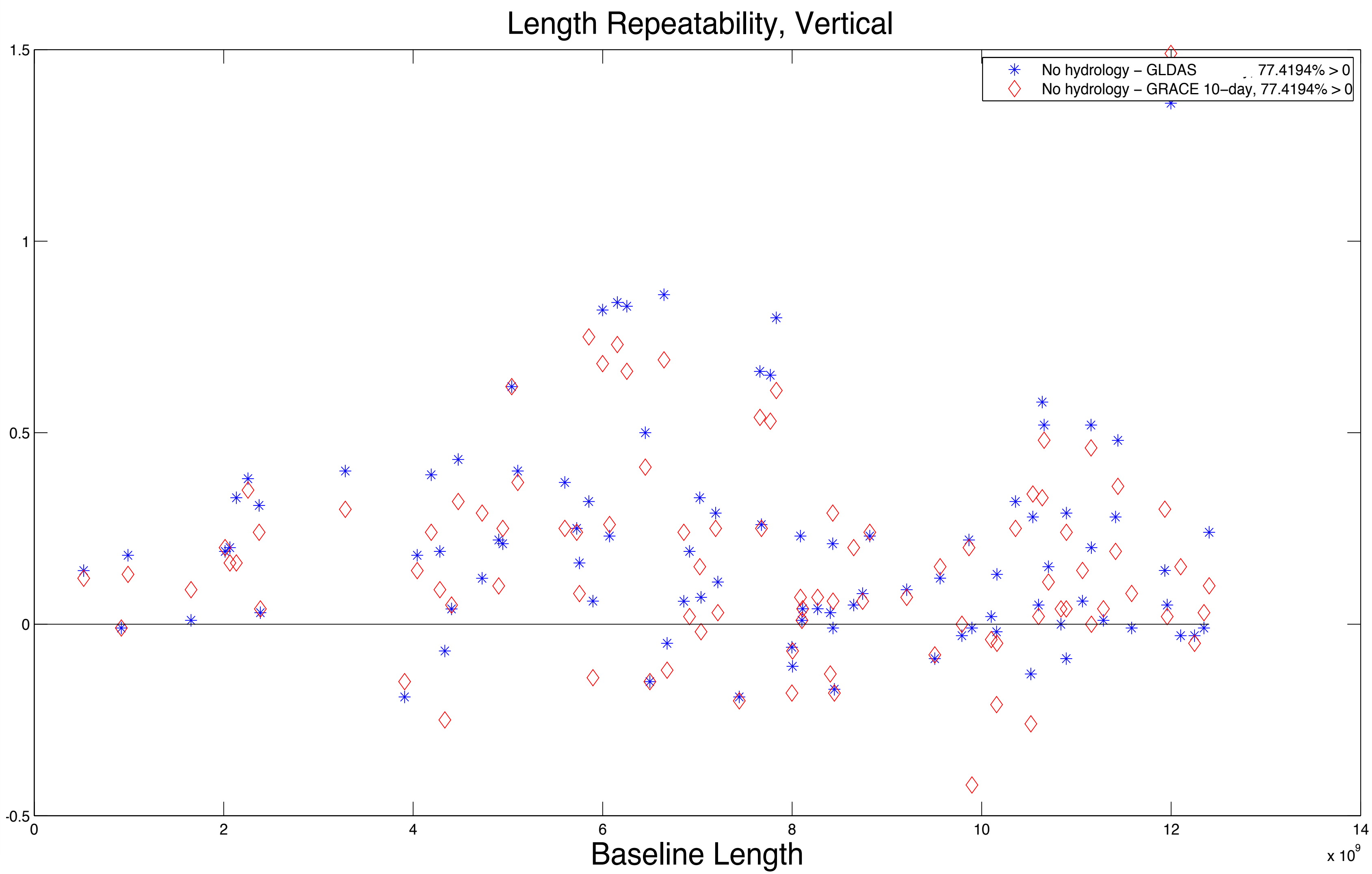
SOLVE Solution for Site (UEN) Time Series

- Based on the 2011a TRF/CRF quarterly solution
- Estimate site positions for each session instead of global positions/velocities
- Apply no-net translation constraint for session network stations
- Used the weekly operational R1 and R4 network sessions

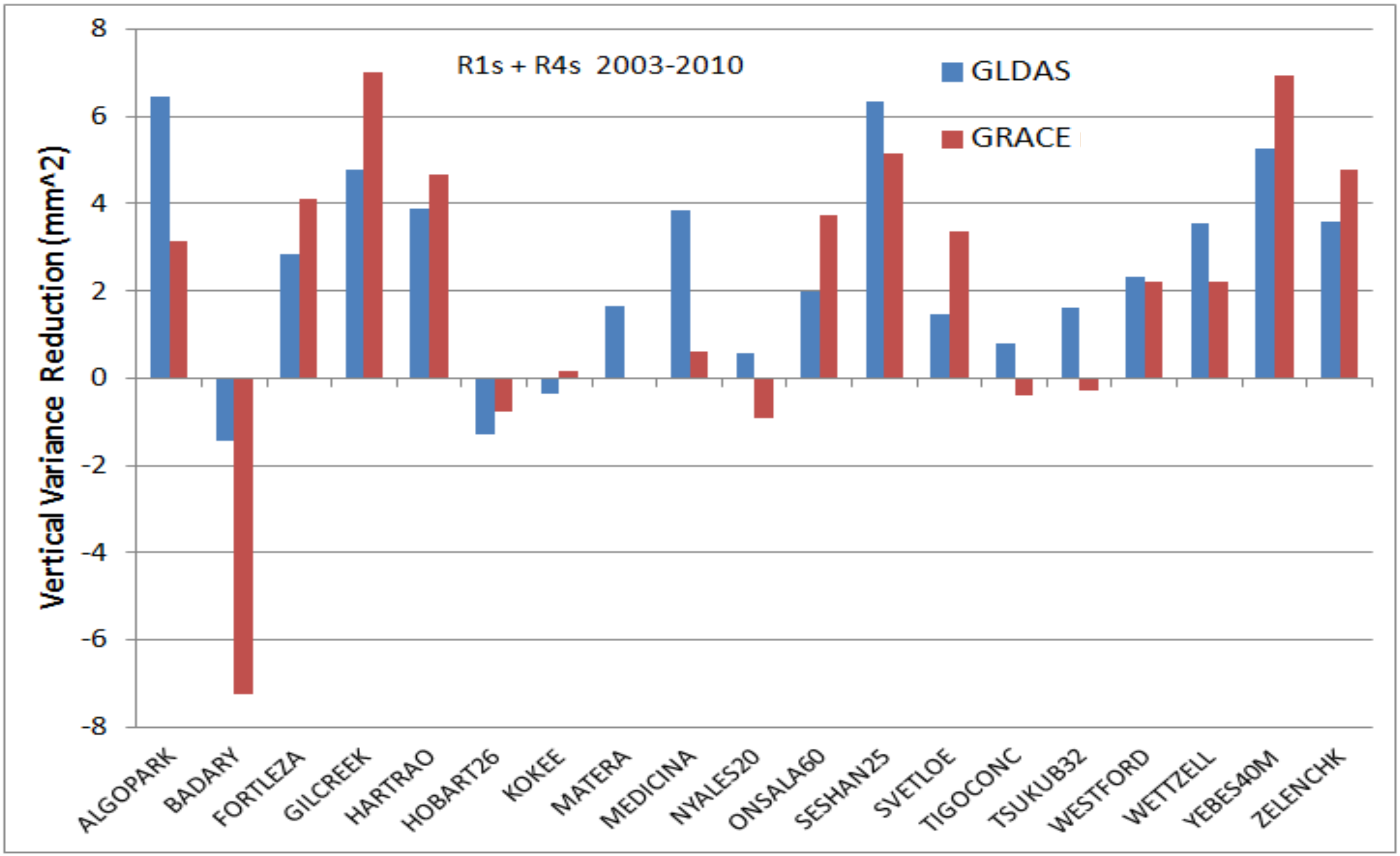
Hydrology Loading Solutions

1) No loading applied
2) GLDAS loading series applied
3) GRACE loading series applied

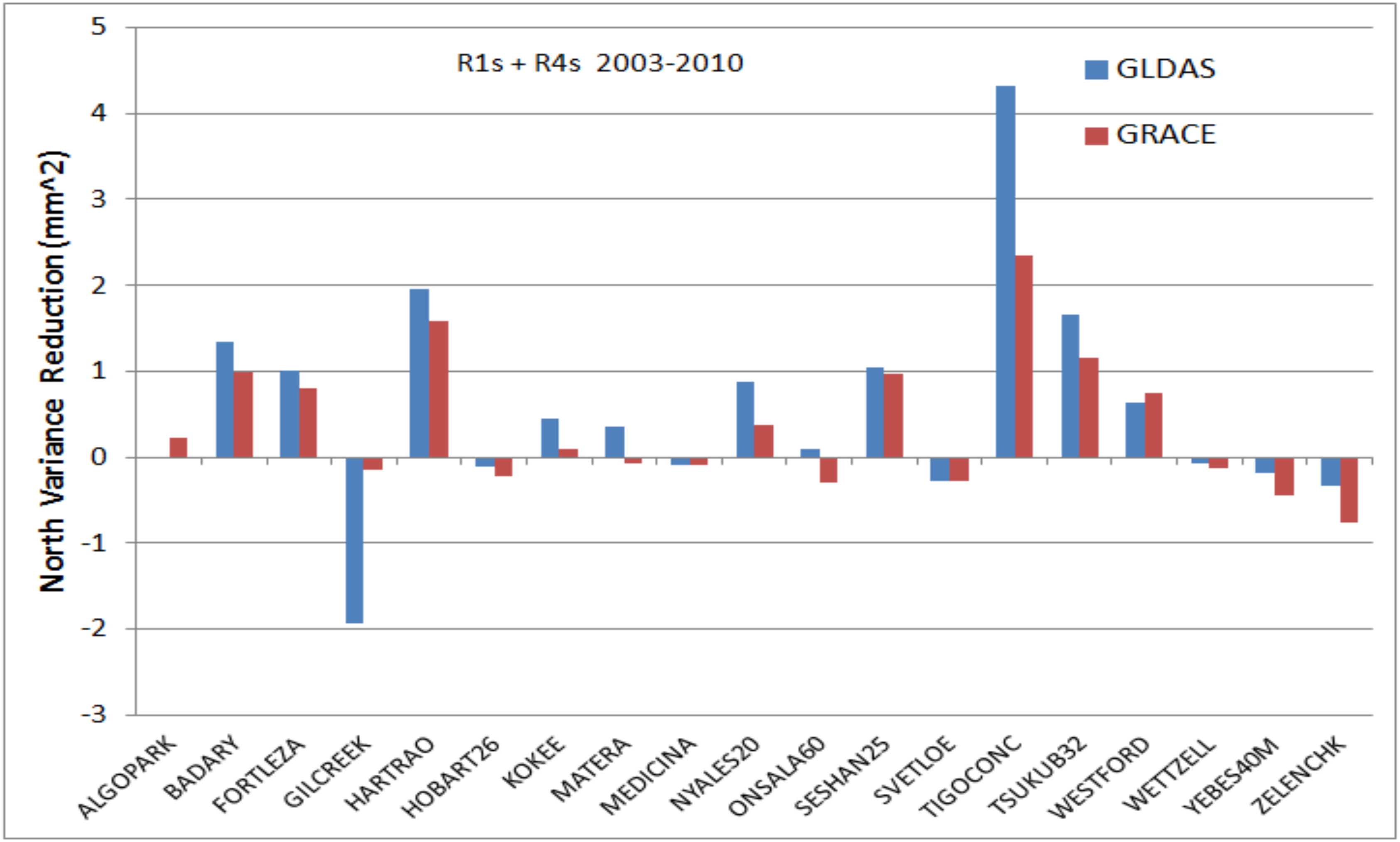
Length Repeatability Improvement



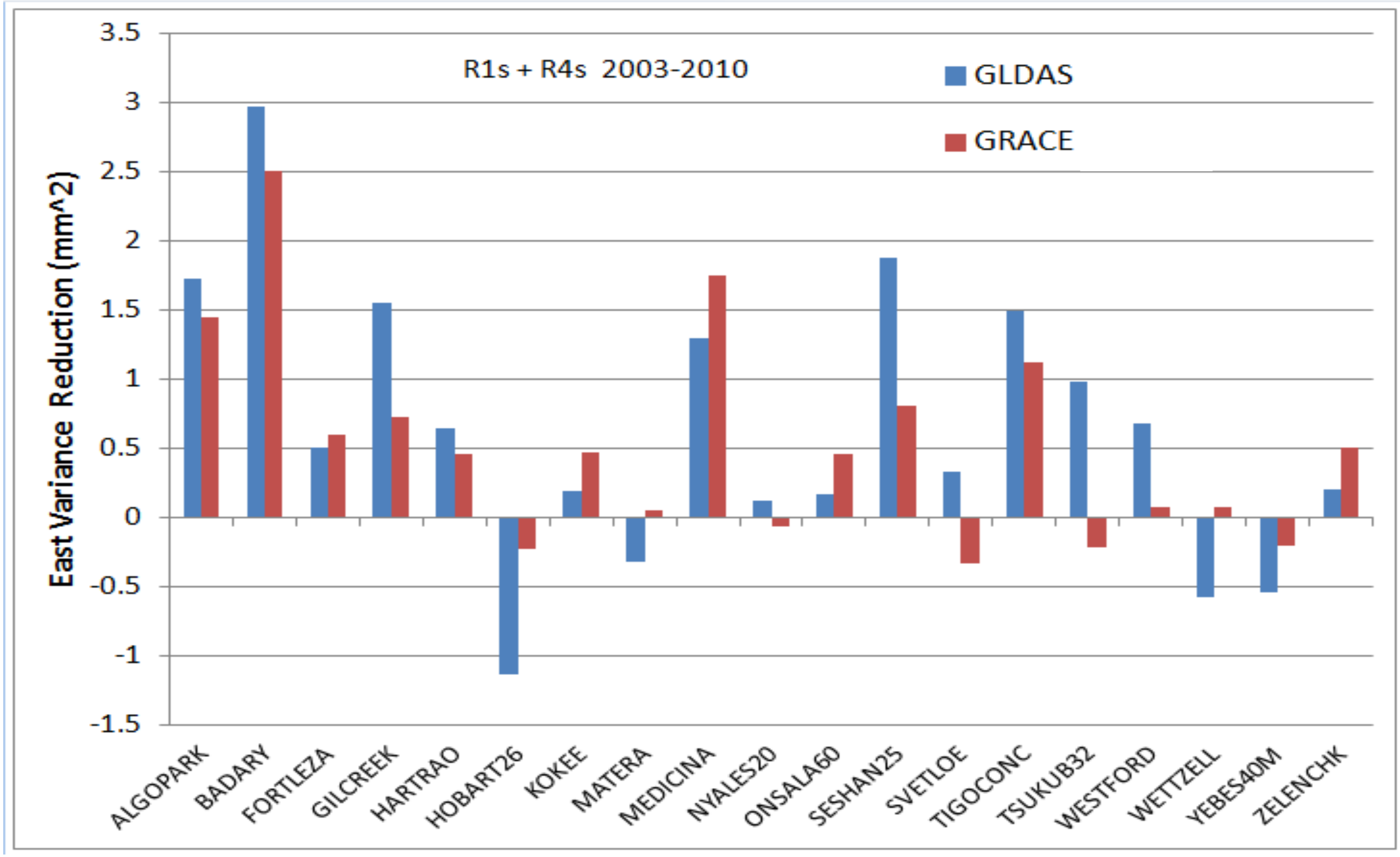
Vertical Improvement



North-South improvement



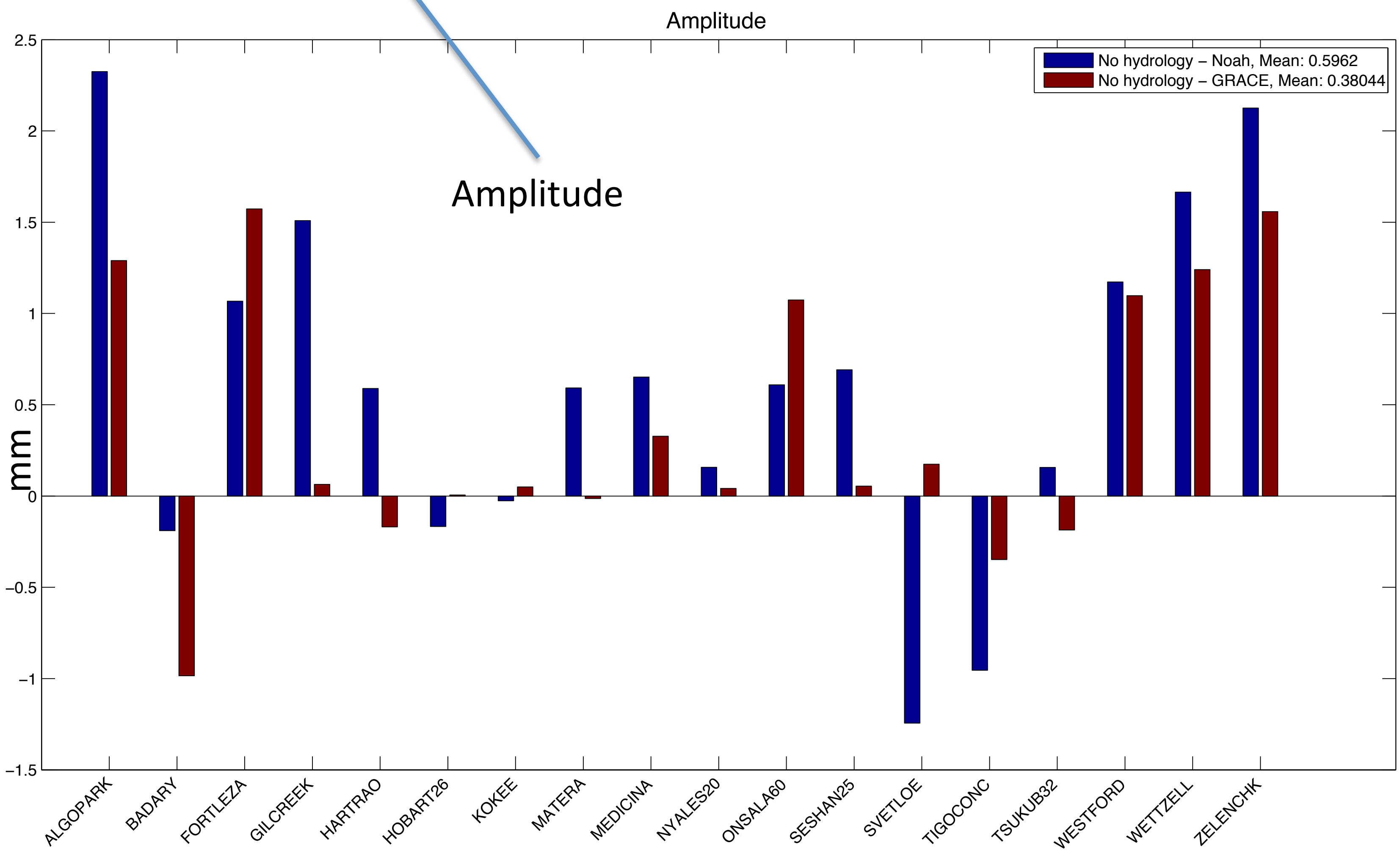
East-West improvement



Reduction in Amplitude using least squares

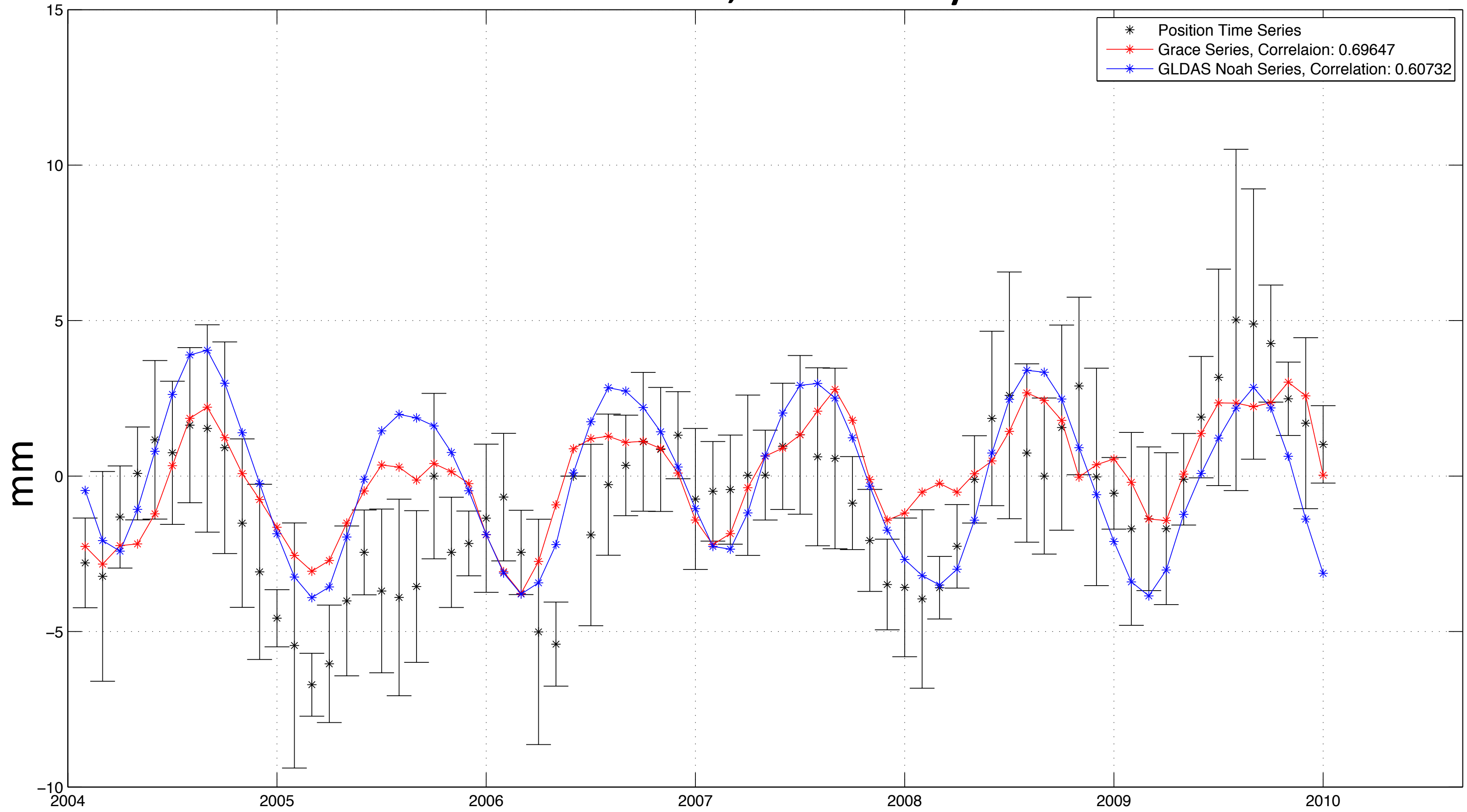
$$f(x) = a + bx + c\cos(2\pi[x+d]) + e\mathrm{H}(x - \mathrm{jump\_date})$$

Amplitude



Correlation between vertical position time series and hydrology series for NOAH and GRACE

Wettzell, Germany



Further investigations

- Make a GLDAS NOAH solution using the full 3-hour model.
- Make GRACE solutions using areas with permanent frost and without masking out the oceans.
- Use new GRACE solutions with all contributions, including the atmospheric part

Conclusions

- Both the GLDAS and GRACE hydrology loading series reduce VLBI vertical and horizontal scatter.
- Most sites show good correlation between GLDAS and GRACE vertical loading series.
- We are still investigating
  - Anomalous behavior of loading series at several sites
- We are working on a service to provide hydrology loading series for the VLBI sites using the GLDAS model since it goes all the way back to 1979.
- We are writing a paper on hydrology loading.

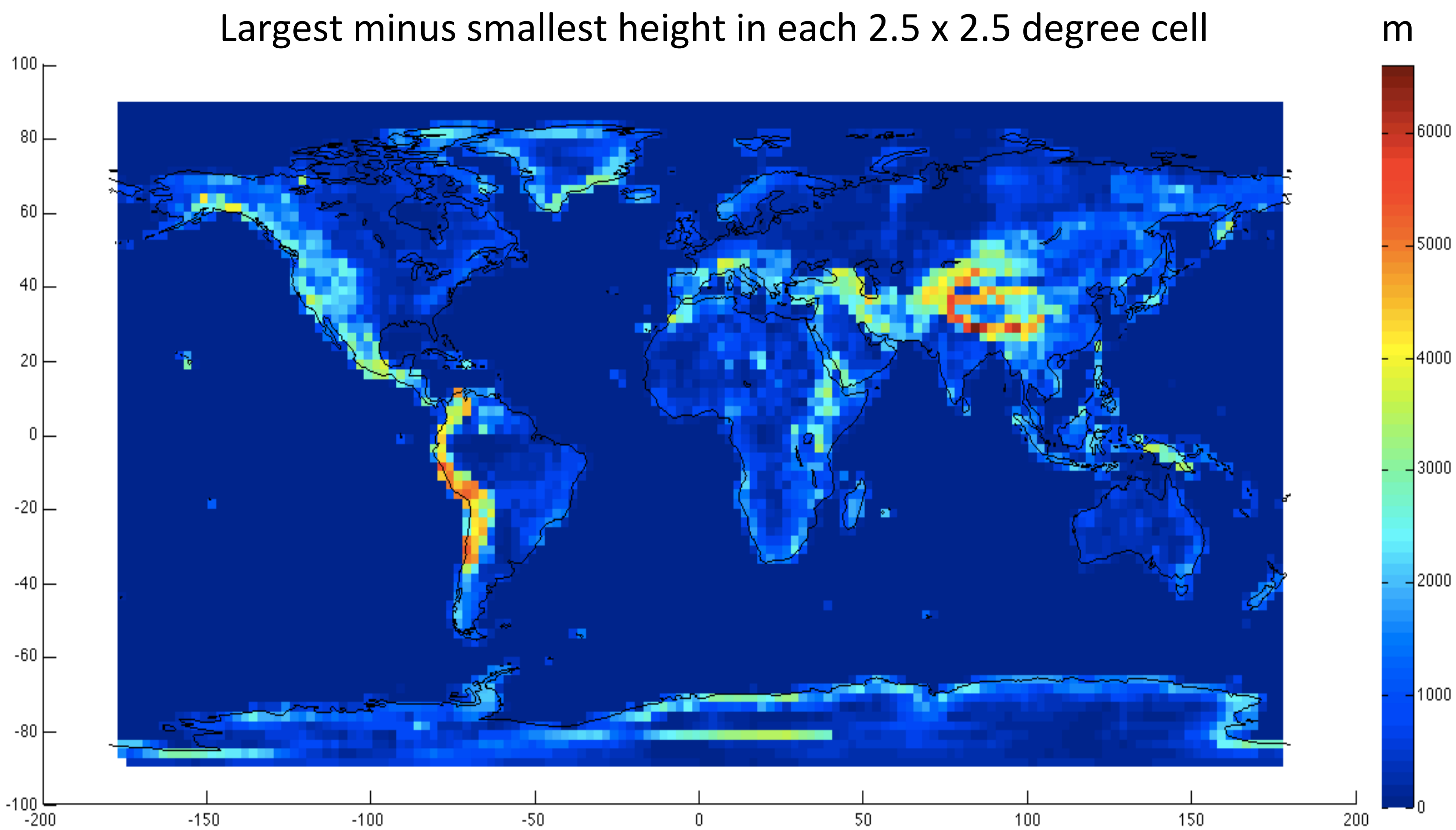
Pressure loading

- Topographic errors in the NCEP model will imply errors in the computed pressure loading series [van Dam et al. 2010]
- NCEP reanalysis data is computed for the gridpoints at a 2.5° x 2.5° resolution.
- To get the pressure series at another point the pressure is interpolated from the gridpoint.

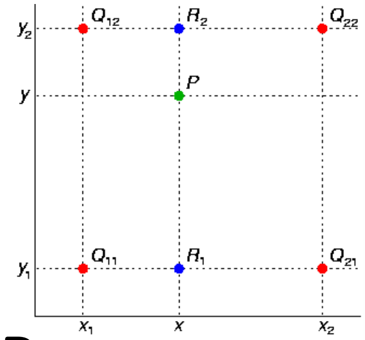
Topography data

- ETOPO5 topography data is used and resampled to a 0.25 x 0.25 degree resolution.
- The ETOPO5 topography data is provided by the National Geophysical Data Center.
- Mountainous areas show a large topographic variation which imply errors in our pressure loading calculations.

ETOPO5 topography height variation



Height adjustment procedures



- To get the pressure series at a given topographic point:
  1) Extrapolate the four surrounding NCEP gridpoints to the height of the topographic point
  2) Use bilinear interpolation to get the pressure series at the topographic point

$$p(z) = p_0 \left(\frac{T_0 - \Gamma \Delta z}{T_0} \right)^{\frac{g}{R\Gamma}}$$

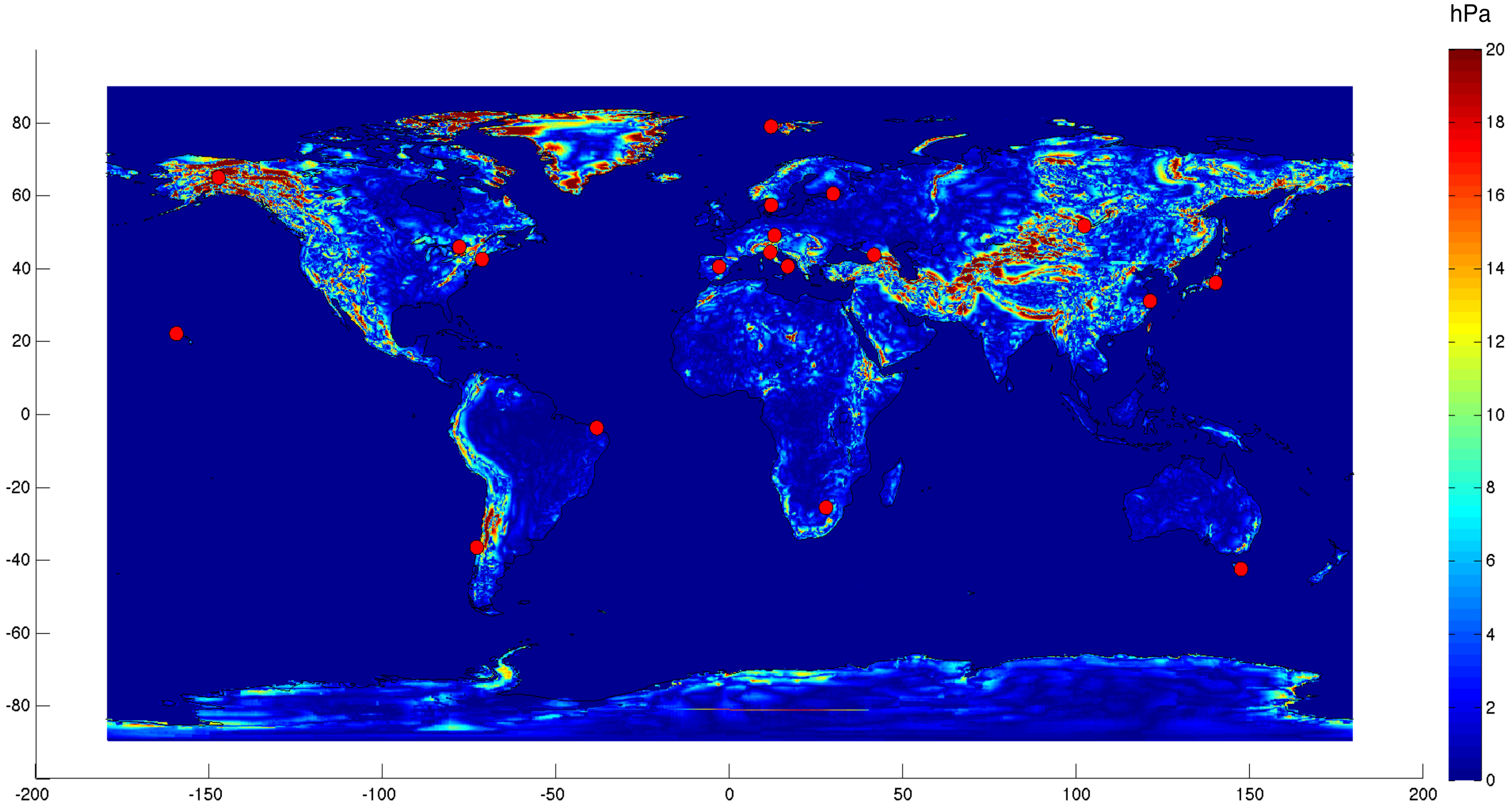
Γ = lapse rate of temperature
Δz = difference in geopotential heights
R = the gas constant
g = acceleration due to gravity

- Example: A change in height of 2000 meters corresponds to a change in pressure of 200 mbar

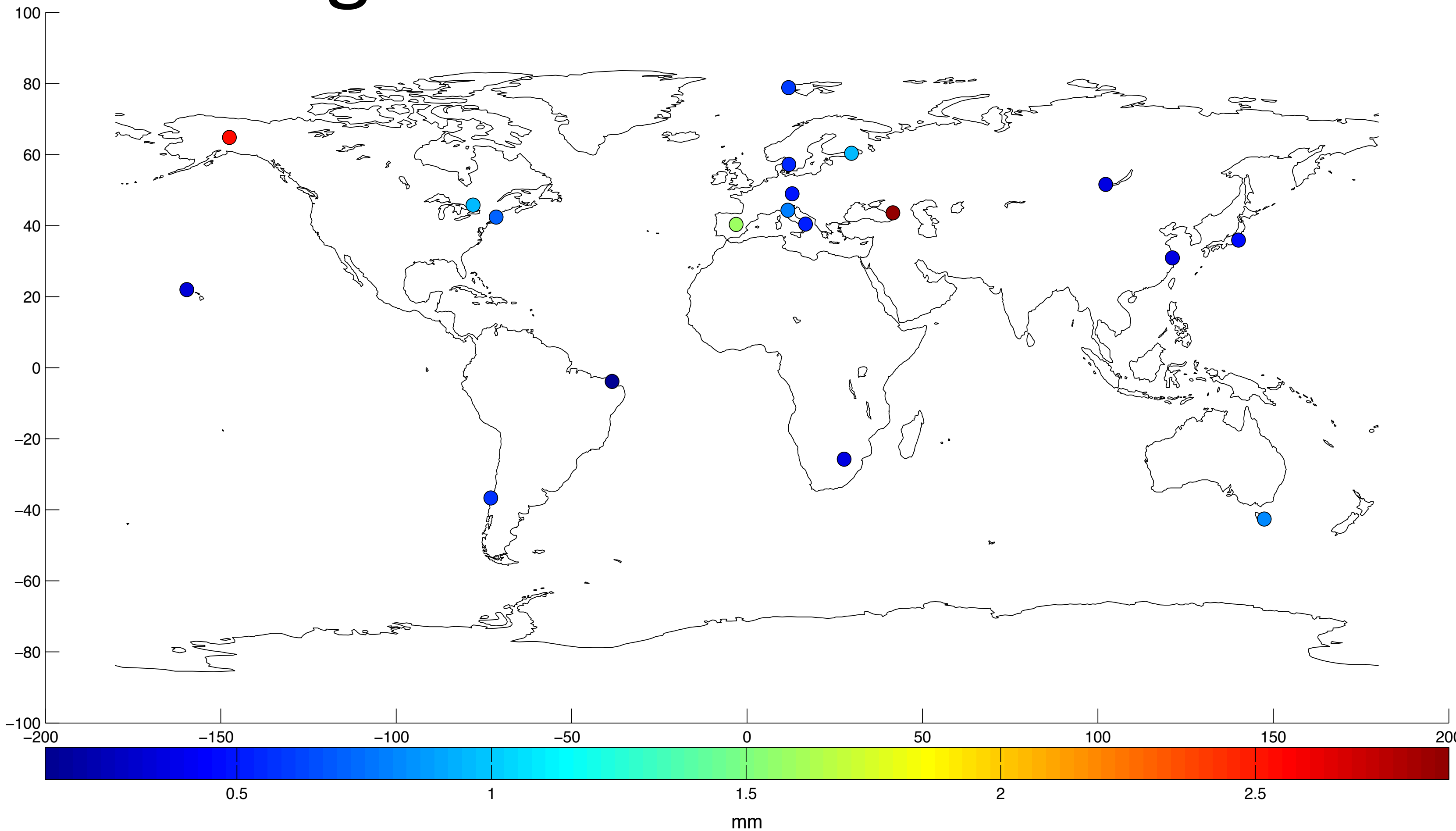
Pressure loading series

- We create two high-resolution pressure series from the original NCEP pressure data.
  1) NCEP_Fine – interpolated NCEP pressure data without height adjusting the series
  2) NCEP_Topo – height adjusted and interpolated series
- NCEP_Fine - NCEP_Topo will have a seasonal character since the temperature has a seasonal signal.
- There will be a bias between the two series.

Standard deviation of the difference NCEP_Fine – NCEP_Topo

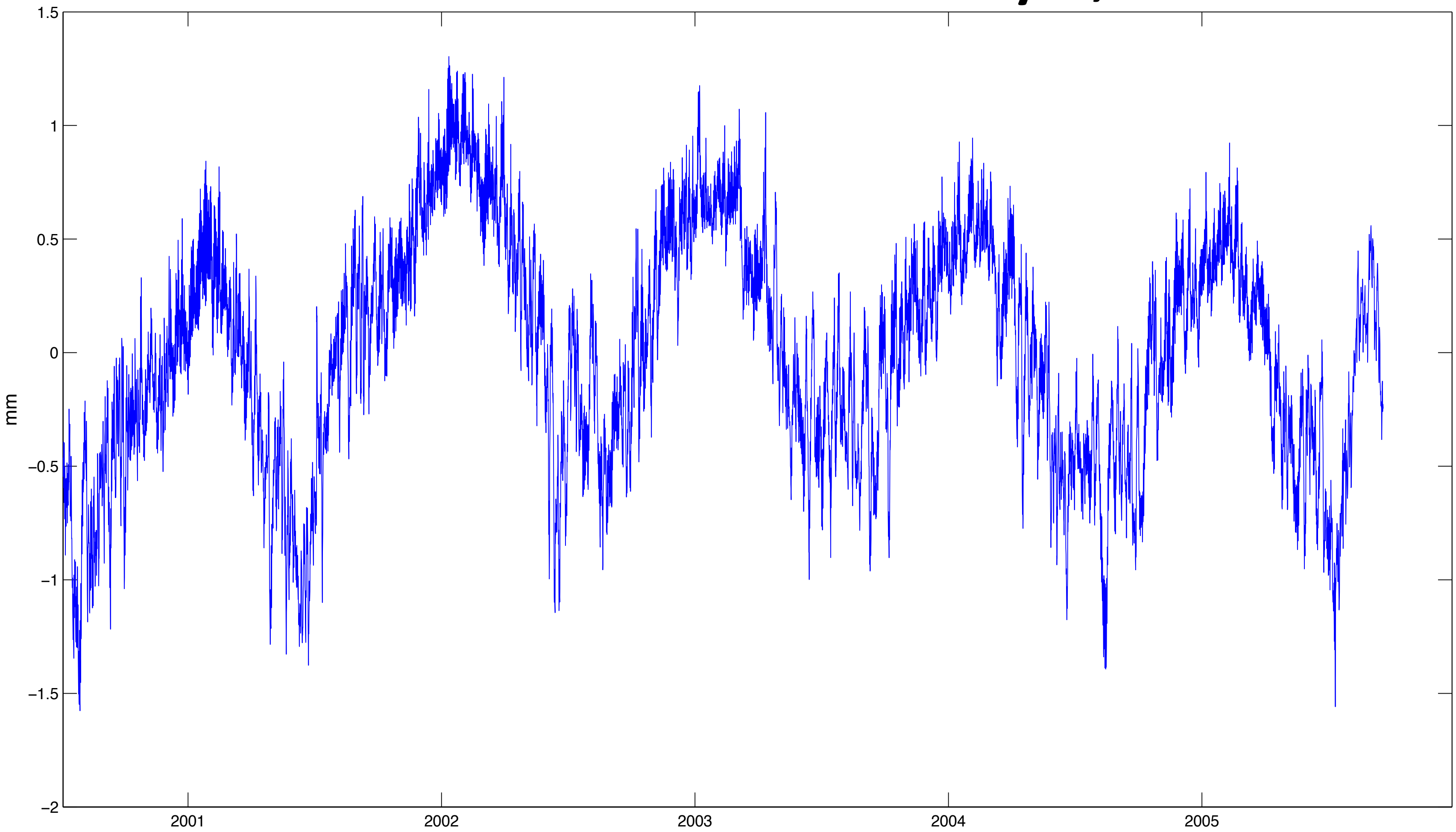


Topographical errors in the pressure loading series for the R1s and R4s



Errors are given as the peak-to-peak distance for the loading difference

Pressure loading difference for the VLBI site in Zelenchukskaya, Russia



Other sources of pressure

- ECMWF provide pressure data at resolutions as fine as 0.25 x 0.25 degrees
- This higher resolution means that the corresponding surface is more accurate than for the NCEP model
- The topographic errors using the ECMWF model with a 1.5 x 1.5 degree resolution are about half the size of the errors when using NCEP

Conclusions

- There are topographic errors in the vertical pressure loading series that are at most 2-3 millimeters peak-to-peak for the R1 and R4 sites.
- The topographical errors will be smaller if the pressure model has a more accurate surface.
- Topographic errors are smaller for ECMWF than NCEP since ECMWF uses a more accurate topography